Title:
Resilience of rail support systems: the use of plastic sockets

Authors:
William Coombs, School of Engineering and Computing Sciences, Durham University
Yousef Ghaffari Motlagh, School of Chemical and Process Engineering, University of Leeds

Abstract:
The use of such plastic inserts and other soft fastening solutions in pre-stressed concrete sleepers and crossing bearers has become widespread within the UK, Europe and the rest of the world. The stiffness of these inserts is typically an order of magnitude lower than that of the surrounding concrete and their inclusion leads to significant stress concentrations. This article quantifies the magnitude of the stress raiser and explores the potential of these elevated stress levels to lead to fracture development.

## Introduction

The UKs rail infrastructure currently supports 1.3 billion passenger journeys and 100 million tonnes of freight each year. The freight transport alone contributes £870 million to the UK economy [1]. The vast majority of this 32,000km of rail infrastructure is supported by pre-stressed concrete sleepers (PCSs) and crossing bearers (CBs). These concrete members provide lateral restraint and vertical support to the running steel rails. The PCSs and CBs are in turn supported on three sides by track ballast; crushed stone 30-50mm in diameter. Since their introduction in the 1950s, PCSs have superseded traditional wooden sleepers in new track and Network Rail (NR) replaces approximately 200,000 timber sleepers each year with PCSs. However, despite the reliance of the UKs rail network on these concrete structures, and the simplicity of their geometry, surprisingly their structural behaviour is poorly understood. PCSs are attached to the running-rail (and other components, such as the electrified third rail) through cast-in-place inclusions. Two types commonly used are: steel shoulders, designed to clamp the rail through a reaction spring, and threaded plastic inserts to allow in-situ bolting of components (such as the Vossloh dowel fastening solution [2]). The plastic inserts are soft relative to the surrounding concrete (10-40 times lower Youngs moduli) and create local stress concentrations exaggerated by high longitudinal pre-stressing. These concentrations have the potential to initiate longitudinal fractures that can significantly reduce the support system's designed 50-year service life. In order to maintain a safe, reliable and resilient rail network it is essential to understand how the concrete support systems can be designed to future proof them against ever increasing structural demands.

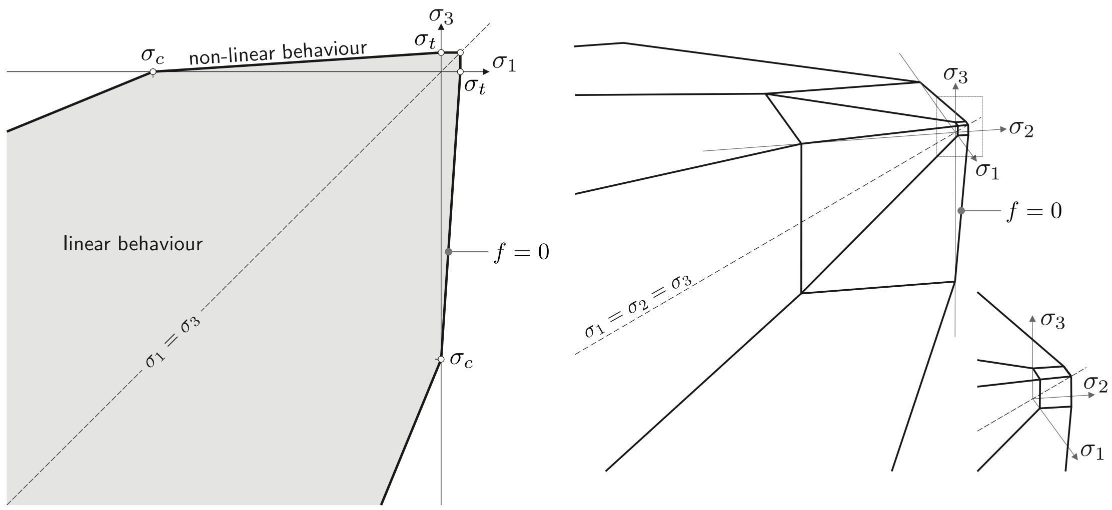
The majority of previous work on the structural behaviour of sleepers has focussed on high impact loading and rail-seat deterioration [3,4]. However, there have been a few recent studies that have focused on the initiation of fracture around the rail fastener bores. One of these with particular relevance to this work is a 2012 study by Rezaie *et al.* [5] focusing on this behaviour on monoblock sleepers used in Iranian railways. A more recent study by Rezaie and Farnam in 2015 [6] looks at the effect of fracture initiation length on the integrity of the sleepers. In particular their work links to this research by investigating the level of pre-stress at which fracture initiation takes place and the following the development of the fracture under pre-stress loading.

In the 2012 study of Rezaie *et al.* [5], it was found that before track operation, longitudinal fractures were observed originating from the plastic insert positions towards the centre and ends of the sleeper. They found that when the pre-stressing forces were applied, significant tensile stresses in the direction perpendicular to the longitudinal axis of the sleeper were produced around the plastic sockets - reaching approximately 80% of the tensile strength of the concrete. The conclusion of the study was that environmental factors such as freezing water and debris in the bore could lead to the initiation of fractures. The 2015 finite element analysis study of Rezaie and Farnam [6] concerned the propagation of longitudinal fractures under a three-point bending test. However, in that study the fractures were wished-in-place rather than allowing the numerical analysis to dictate the location of the initial fracture.

This article describes a numerical framework that can be used to assess any potential material instabilities (that is, fracture initation) that arise around cast-in-place inclusions within a concrete body. In particular the numerical analyses presented in this paper focus on a plastic socket, similar to the Vossloh dowel fastening solution [2], subjected to pre-stressing loads and quantify the point at which material instabilities first arise.

## Material failure

In this work we use a relatively simple material model for the behaviour of the concrete cast within the framework of elasto-plasticity. The failure of the concrete is controlled by a yield envelope formulate in stress space that separates linear elastic behaviour from non-linear elasto-plastic behaviour. The yield envelope comprises of three planar surfaces in principal stress space: (i) a Mohr-Coulomb (M-C) plane in the compressive region, (ii) a Rankine cut-off in limiting the allowable tensile stress and (iii) an additional M-C surface linking the two regions. This failure surface, $f = 0$, is shown in Figure 1 in both biaxial stress space and principal stress space. The surface requires the specification of the concrete's uniaxial compressive strength, uniaxial tensile strength and friction angle in the compressive regime. The tensile strength of the concrete can normally be assumed to be 10-15 times smaller than the compressive strength. In this work we assume that the compressive strength of the concrete is 40MPa, the tensile strength 2.7MPa and the friction angle 37°. Although this surface controls failure and the onset of permanent deformations it does not directly specify when a fracture will form.




(a) (b)

Figure 1: Non-linear concrete model in: (a) biaxial stress space (linear grey area and non-linear thick black line) and (b) principal stress space.

## Fracture initiation

Since the 1958 and 1962 papers by Hill [7,8], there has been a strong interest in the mathematical identification of instabilities that can be predicted purely from the characteristics of the material models that we use to represent the behaviour of engineering materials. Failure indicators in materials can be grouped into two categories: (i) loss of stability and (ii) fracture [9]. The key difference is that in the case of fracture a jump is observed in the strain field. The development of a fracture can be detected through investigating the stiffness of the parent material. More technical details of the fracture initiation method can be found in [10].

## Numerical computations

Here a single plastic socket is analysed with geometry similar to that of a Vossloh dowel fastening solution [2]. Only a local region of concrete surrounding the socket was modelled using finite elements. The elastic material constants for the concrete material model are a Young's modulus of 45GPa and a Poisson's ratio of 0.2, the strength parameters were detailed earlier. The plastic socket modelled as an isotropic linear elastic material with a Young's modulus of 1.1GPa and a Poisson's ratio of 0.2. Note that here the plastic socket is 40 times softer than the concrete. The finite-element analyses were conducted using a bespoke finite-element code developed at Durham [11].

The volume of concrete modelled had a height of 165mm and a width and breadth of 250mm; typical sleepers and bearers have cross sections ranging between 140-205mm in height and 250-380mm in width and are typically subjected to an average compressive longitudinal pre-stress of between 11 and 15MPa. Here the analysis applied a compressive longitudinal stress of 11MPa over 100 loadsteps. Due to symmetry only one quarter of the problem was analysed, as shown in Figure 2. The central plastic socket was modelled having a total length of 165mm, a uniform internal diameter of 20mm and an external diameter of 39mm at the top surface of the mesh, tapering to a diameter of 31mm over 25mm down the length of the socket. Full displacement compatibility was assumed between the concrete and plastic elements and only pre-stressing loads were considered.

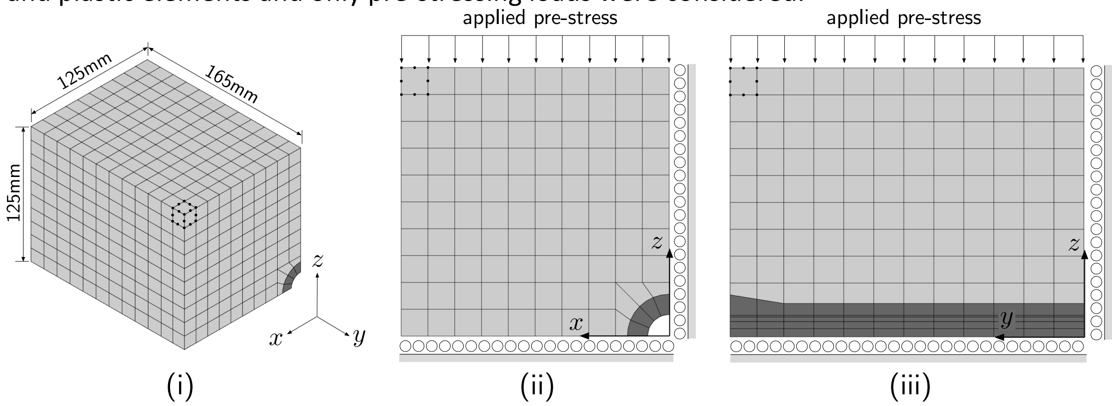



Figure 2: Finite-element mesh: (i) three-dimensional view of the mesh, (ii) plan view and (iii) side elevation looking in the positive x-direction. The light and dark shaded elements are concrete and plastic, respectively. The circles on parts (ii) and (iii) indicate roller boundary conditions.

Figure 3 shows the evolution of failure points as the pre-stress is increased, as shown by the red circles. Material first begins to fail at a pre-stress of 3MPa with the failed material located at the longitudinal limit of the plastic socket. Once the pre-stress has reached 6MPa the failure zone extends the full length of the plastic socket and it is at this point that fracture initiation is first predicted. Once a pre-stress of 11MPa has been reached the failure region extends approximately one radius of the plastic socket into the concrete material.

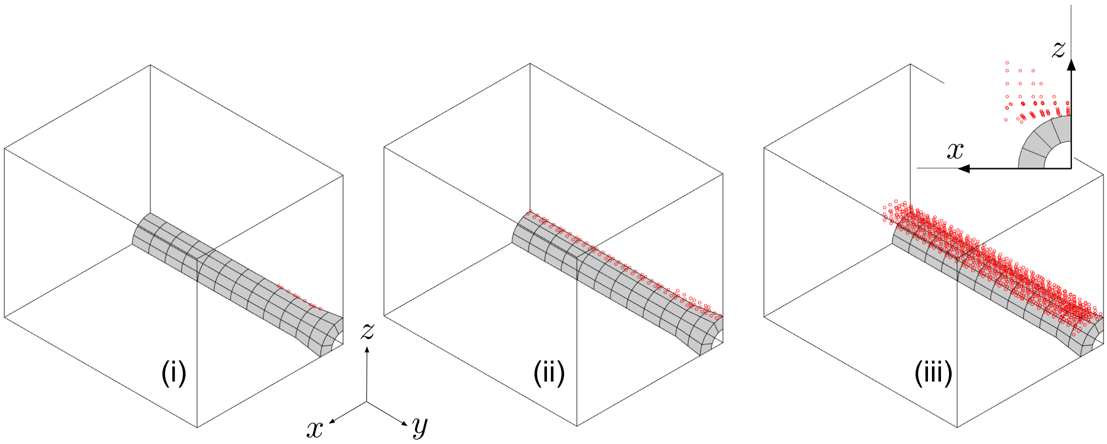



Figure 3: Failure points at: (i) 3MPa, (ii) 6MPa and (iii) 11MPa of pre-stress.

Figure 4 shows three predictions of the instability normal directions a pre-stress of 11MPa based on: (i) the most tensile principal stress, (ii) the most tensile plastic strain and (iii) the instabilities predicted by the fracture criterion discussed earlier. Note that any fracture planes will develop perpendicular to these normal directions. Both the stress and plastic strain directions have been scaled according to their magnitude. It is clear that both the locations and directions of the instabilities differ for the three methods, the most noticeable difference being between the proposed fracture criteria and the other methods.

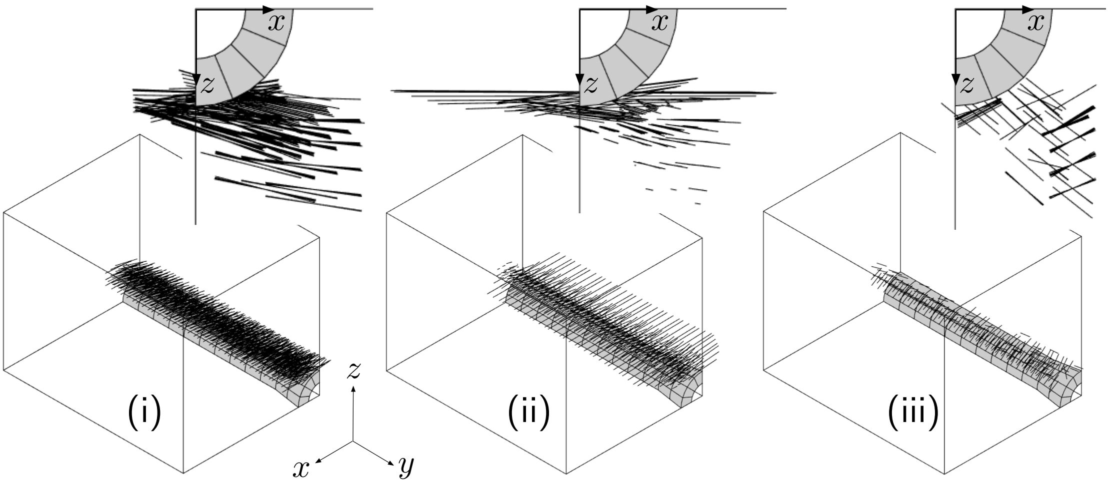



Figure 4: Fracture plane for: (i) max tensile stress, (ii) max plastic strain and (iii) instability analysis

An advantage of the proposed method is it allows us to not only determine the direction of the fracture but also its nature. In this case the fracture appears to behave as a dilative shear band starting from the surface of the plastic socket.

Finally, Figure 5 shows an X-Ray Computed Tomography (XRCT) scan of an experimental test set up to match the numerical analysis. XRCT equipment combined with image reconstruction produces a 3D image of the sample, which allows visualisation on the internal structure of a material. In the figure dense material appears as light grey and voids are black. A single longitudinal fracture is visible in both images consistent with the general nature of the fracture predicted by the numerical analysis.

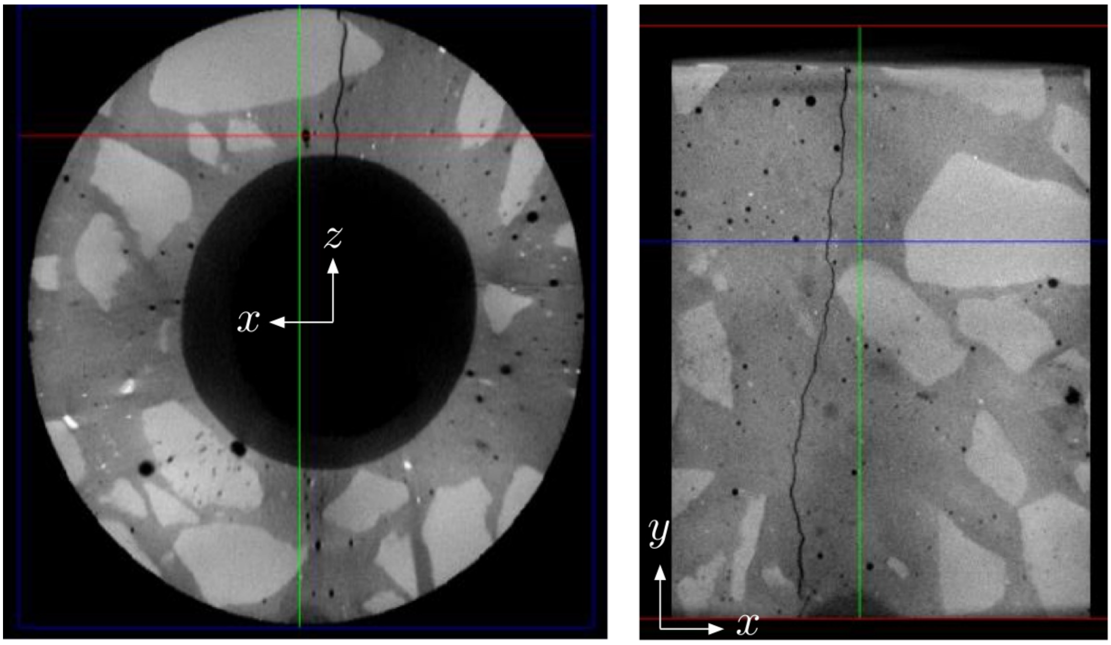


Figure 5: XRCT images of the socket fracture

## Conclusion

The analysis presented in this paper considered a plastic dowel with geometry typical of those used to attach components to pre-stressed concrete sleepers and crossing bearers. It was observed that fractures first develop at a pre-stress of approximately 6MPa once a failure zone has developed through the full depth of the concrete. The fracture appears to behave as a dilative shear band starting from the surface of the plastic socket. A noticeable difference was observed between the directions predicted by the proposed fracture criterion and those obtained from other methods. Based on the analyses presented in this paper, the use of plastic inserts within pre-stressed concrete components increases the potential for longitudinal fracture development. These initial fractures, however small, have the potential to be subsequently extended through track loading or environmental factors.

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